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Fluidized bed combustion and fragmentation of wet sewage sludge

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ABSTRACT

Thermo-chemical conversion of sewage sludge in fluidized beds is an attractive path to reduce the amount of landfilled waste and to mitigate the environmental impact related to sewage sludge disposal. The present study is directed to the characterization of the devolatilization and combustion patterns of lumps of wet sewage sludge in a fluidized bed combustor, with a focus on particle segregation, morphological changes and comminution phenomena associated with in-bed drying, devolatilization and char burn-out. The experimental investigation was carried out with the aid of different and complementary experimental techniques. The phenomenology of devolatilization and char burn-out has been investigated in an optically accessible quartz bench-scale fluidized bed combustor. Self-segregation of fuel lumps to the top of the bed during devolatilization was recorded. Stratified combustion of the emitted volatiles was observed to take place above the bed surface in a flameless fashion. Morphological changes of wet sewage sludge after in-bed devolatilization and burn-out has been accomplished by SEM/EDX and image analysis. The formation of balloon-like particles consisting of a porous outer layer enclosing a big single cavity is reported. The physical and chemical features of ash and char particles have been characterized. Particle fragmentation phenomena have been characterized by varying the oxidative vs. non-oxidative nature of the fluidizing gas, the initial size of the fuel particle, the bed material size, the fluidization velocity. Particle fragmentation occurs mainly during drying and pyrolysis/devolatilization and is very limited during char burn-out. Fragmentation is reported to take place when the initial size of the lump of wet sludge exceeds a critical value which depends on the bed material size and excess gas superficial velocity. Particle fragmentation is strongly affected by the size of bed material and moderately by the excess gas superficial velocity.

1. Introduction

Disposal of sewage sludge is a challenging environmental issue emphasized by the continuously increasing volumes of sewage sludge generated by municipal wastewater treatment plants. The environmental legislation is becoming more and more restrictive as regards landfilling of this biodegradable waste. The progressive decrease of the use of sludge in agriculture, that can only be considered under very well controlled conditions due to the presence of heavy metals and pathogens, further stimulates the search for alternative disposal pathways. In this context, thermochemical conversion of sludge is gaining broader consideration. Combustion and co-combustion are currently indicated as viable processes to dispose of sewage sludge [1], stimulated also by the consideration that using sewage sludge as a substitute fuel may contribute to the net reduction of CO_2 emissions to the atmosphere, due to its biogenic nature. Technologies based on fluidized bed combustion and gasification are attractive options, due to their inherent operational flexibility, high efficiency, low pollutant emissions, ability to effectively accomplish destruction of micro-pollutants and pathogens [1–7].

Despite several sewage sludge combustion plants are already in operation, there is still a lack of fundamental understanding of the basic mechanisms underlying thermochemical conversion of sewage sludge in fluidized beds [8–15]. The interaction of wet lumps of sewage sludge with the hot fluidized bed, the morphological and physico-chemical changes of sludge particles during drying, devolatilization and char burn-out, the emission and burn-out of volatile matter in and above the fluidized bed, the extent and patterns of particle comminution during fluidized bed conversion are still poorly characterized. In particular, attrition and fragmentation of sludge particles during drying, devolatilization and char burn-out are expected to play a key role in the operation of industrial units. The loading of fines in the flue gas, the effectiveness of flue gas de-dusting and the closely associated emission of particulates at the exhaust are expected to be critically dependent on the extent of particle comminution. Moreover, the very ability to establish a stable bed inventory by accumulation of fuel ash, a prerequisite for stable and trouble-free operation of fluidized bed combustors

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and gasifiers, is bound to be largely affected by particle comminution. Attrition and fragmentation are critically influenced by the twofold nature of sewage sludge, the biogenic component being intimately associated with an inorganic component whose nature is largely influenced by additives used for wastewater stabilization and conditioning.

The experience gained with other biogenic fuels characterized by high moisture and volatile matter contents indicates that fluidized bed combustion is characterized by the following features: (i) fuel particles undergo pronounced segregation phenomena during devolatilization [16,17]: coarse fuel particles quickly rise to the bed surface under the action of the volatiles bubbles, "floating" thereon until devolatilization is complete; (ii) extensive post-combustion of volatile matter occurs in the splashing region and/or in the freeboard [18]; (iii) fuel particles yield, upon devolatilization, a char characterized by large porosity, often anisotropic, and large intrinsic reactivity, as compared with char from coals; (iv) the residual char particles are mechanically weak and subject to extensive attrition and fragmentation as they interact with the vigorously bubbling fluidized bed [19].

The present paper aims at a better understanding of the basic phenomena associated with fluidized bed combustion of wet lumps of sewage sludge. In particular, particle segregation, volatile matter emission and burn-out and char combustion, attrition and fragmentation have been characterized by a combination of different and complementary experimental techniques. Devolatilization/pyrolysis and char burn-out have been analyzed by visual observation of single lumps of fuel in an optically accessible fluidized bed reactor and by analysis of the time series of the concentrations of gaseous species measured at the exhaust. Particle attrition and fragmentation have been characterized by recording the number and size of generated fragments at different stages of conversion, and have been related to the initial size of the fuel particle and to the operating conditions of the bed.

2. Experimental

A stainless steel atmospheric bubbling fluidized bed combustor 41 mm ID and 1 m high was used for pyrolysis/combustion and attrition/fragmentation experiments (Fig. 1A). A 2 mm thick perforated plate with 55 holes (ID 0.5 mm) disposed in a triangular pitch was used as gas distributor. A 0.6 m high stainless steel column was placed under the distributor, serving as gas preheater and equalizer. Two semi-cylindrical 2.2 kW electric furnaces were used for heating the fluidization column and the preheating section. Bed temperature, measured by means of a chromel–alumel thermocouple located 4 mm above the distributor, was regulated by a PID controller. The upper section (0.4 m high) of the freeboard was kept unlagged in order to minimize fines post-combustion in this section. Gases were fed to the column via high-precision digital mass flow-meters. The fluidization column was exhausted to the atmosphere. A stainless steel circular basket could be inserted from the top in order to retrieve fragmented and un-fragmented particles from the bed. The gap between the column walls and the basket was limited so as to reduce the amount of particles left in the bed when pulling out the basket. A basket mesh of 0.8 mm was used, so that the bed material could easily pass through the net openings. Fragments smaller than about 0.8 mm were lost through the basket net openings. A stainless steel probe located along the freeboard of the fluidization column was used to convey a fraction of the exhausted gases to gas analyzers. A high efficiency cellulose filter was inserted in the line to avoid particle entrainment into the analyzers. The probe, 4 mm ID, was located 0.6 m above the distributor. Data from the analyzers were logged and further processed on a PC equipped with a data acquisition unit.

A quartz atmospheric bubbling fluidized bed combustor was also used for visual observation of the phenomena occurring during fuel particle combustion. The geometrical features and the ancillary equipment of the optically accessible fluidized bed reactor were the same as those of the stainless steel reactor. A rectangular window (about 5×10 cm) was left open along the lateral insulation to enable optical access to the upper fluidized bed and to the lower part of the freeboard. A high-resolution video camera was used for videorecording.

The bed consisted of 180 g of quartz sieved either in the size range 150–300 μm (U_{mf} = 0.02 m/s @ 850 °C) or 400–600 μm (U_{mf} = 0.09 m/s @ 850 °C).

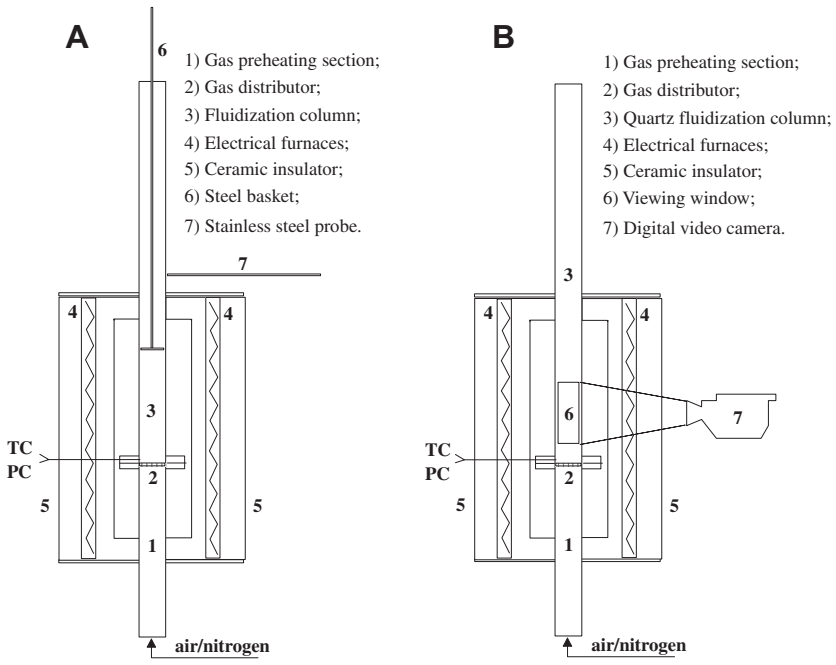

Fig. 1. Experimental apparatus equipped with: (A) stainless steel fluidization column and (B) quartz fluidization column.

Table 1
Properties of the wet sewage sludge.

LHV (as received) (kJ/kg)	1245	Ash analysis (as received) ($\%_w$)	
Proximate analysis (as received) ($\%_w$)		Na	0.019
Moisture	77.8	Mg	0.081
Volatiles	14.5	Al	1.002
Fixed carbon	1.0	P	0.496
Ash	6.7	K	0.085
		Ca	0.547
Ultimate analysis (dry basis) ($\%_w$)			
Carbon	34.7	Ti	0.009
Hydrogen	5.4	Cr	0.019
Nitrogen	5.1	Mn	0.006
Sulfur	0.5	Fe	0.328
Chlorine	1.2	Ni	0.062
Ash	30.1	Cu	0.025
Oxygen (by diff.)	23.0	Zn	0.023

The properties of the sewage sludge are reported in table 1. The heating value and the proximate and ultimate analyses were based on standard ASTM procedures. The inorganic elemental analysis was accomplished by ICP-MS using a Agilent 7500CE instrument after dissolving the fuel samples by means of microwave-assisted acid digestion according to US-EPA 3051 and 3052 methods. The wet sewage sludge, used for the experimental tests, was preliminarily prepared as lumps of spherical shape with size ranging from 5 mm to 30 mm. Air or technical-grade nitrogen were used as fluidizing gas during combustion or pyrolysis tests, respectively.

Pyrolysis or combustion experiments, carried out in the stainless steel reactor, consisted of the injection, from the top of the column, of a single lump of wet sludge into the bed fluidized at a pre-set fluidization velocity and kept at a constant temperature of about 850 °C. The progress of pyrolysis or combustion was continuously monitored by analyzing the time series of the concentrations of the gaseous species measured at the exhaust. Once pyrolysis or combustion were completed, the resulting char or ash particles were retrieved from the bed by means of the basket to determine the number and the size of the residual fragments.

The influence of bed material size has been investigated by comparing results obtained with quartz in the size range 150–300 μm and 400–600 μm, while keeping the excess gas superficial velocity with respect to incipient fluidization at the constant value $U - U_{mf} = 0.38$ m/s. The influence of fluidization velocity on particle comminution has been investigated using bed material in the size range 400–600 μm and varying the fluidization velocity up to 0.8 m/s. The experiments were repeated to collect a statistically significant number of fragments.

The experiments carried out in the quartz reactor consisted of the injection from the top of the column of a single lump of wet sludge into a bed (quartz, 150–300 μm) gently fluidized by air ($U = 0.25$ m/s) and kept at the constant temperature of about 850 °C. Videorecordings of the upper part of the bed and of the freeboard were performed during combustion of fuel particles of different initial size.

Selected ash and char samples were observed under a scanning electron microscope (SEM; Philips XL30 with LaB6 filament) and subjected to energy dispersive X-ray (EDX; Edax DX-4) elemental analysis. Few samples were embedded in epoxy resin and then cut and polished for SEM observation and EDX analysis of particle cross-section.

3. Results and discussion

Fig. 2 reports selected snapshots from videorecordings of combustion experiments of a 2 cm lump of wet sewage sludge (4.24 g) in the quartz reactor. Bed material was quartz sieved in the size range 150–300 μm. The fluidizing gas velocity was set at the relatively small value of 0.25 m/s with the aim of better visualizing the fuel particle motion and the interactive patterns with the bed during combustion and of limiting the possible influence of attrition and fragmentation during these experiments. The upper part of the bed and the lower part of the freeboard are dark red and brighter red, respectively, in the images. The origin of the time scale corresponds to the time at which the fuel particle falls onto the bed surface.

Analysis of the videorecordings suggests that the fuel particle looks darker than the bed for $0 < t < 210$s, it becomes brighter for $210 < t < 290$s and, finally, it assumes nearly the same color of the bed material for $t > 290$s. The different color observed during combustion clearly reflects the fuel particle temperature: smaller than the bed temperature during drying and devolatilization, higher during char burn-out, equal to the bed temperature after complete burn-out. The recognition of the time intervals corresponding to different fuel particle colors provides an estimate of both devolatilization and char burn-out times.

Analysis of the videorecordings highlights that: (i) the fuel particle is segregated in the upper part of the bed during the whole process (drying, devolatilization, char burn-out); (ii) the bed material occasionally overlayers the fuel particle as bubbles burst at the bed surface ($t = 43.68$s, $t = 111.48$s); (iii) volatile matter combustion takes place above the bed in a flameless mode; (iv) there is no evidence of macroscopic fragmentation of the sludge lump, both during devolatilization and char burn-out.

It is worth noting that the fuel particle properties and operating conditions of the experiment were such that devolatilization and drying mainly occur in parallel. Combustion of volatile matter takes place homogenously in the freeboard without hot spots (flameless combustion). The absence of flames of volatile matter under these conditions is attributed to the large amount of moisture present in the fuel particle which reduces both the particle temperature during devolatilization and the heating value of the released volatile matter. Diagnostic techniques typically used to determine devolatilization times – like the flame period and flame extinction time methods – based on the detection of volatile flames around the fuel particles cannot be applied to this kind of fuel. Instead, techniques consisting of the analysis of the time-resolved gas concentration profiles measured during devolatilization/pyrolysis and char burn-out can still be applied [10,15,20,21].

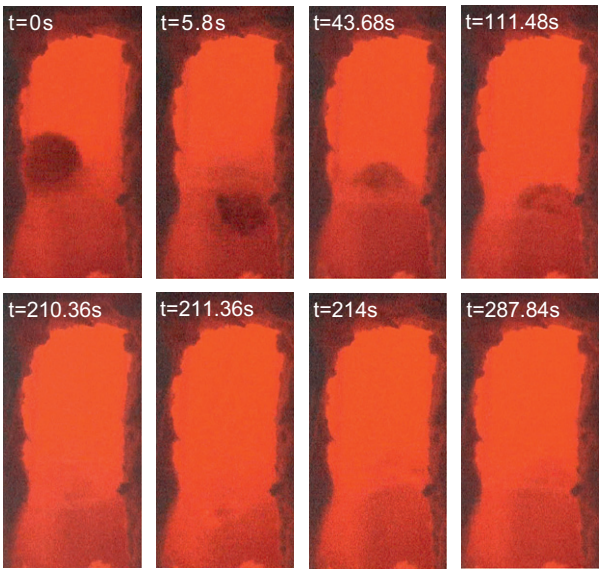

Fig. 2. Snapshots captured during devolatilization and char burn-out of a particle of wet sewage sludge. Fluidizing gas: air; fluidization velocity: 0.25 m/s; fuel particle size: 2 cm; frame rate 25fps.

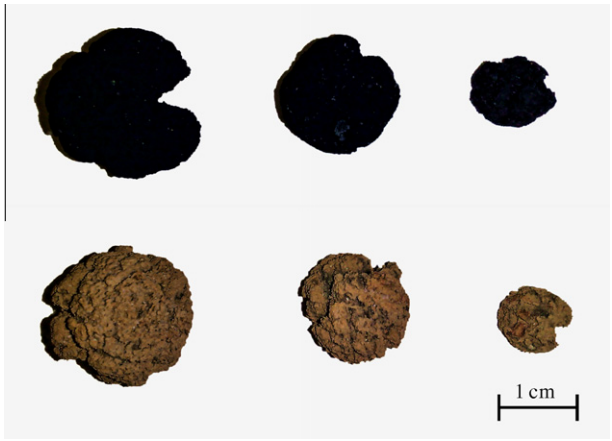

Fig. 3. Images of three sludge particles of about 3, 2 and 1 cm in size respectively after tests of pyrolysis (black particles) and devolatilization and char burn-out (brown particles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Increasing the initial fuel particle size the qualitative combustion pattern remains substantially equal to that reported in Fig. 2, but both the devolatilization and the char burn-out times increase.

Fig. 3 shows micrographs of three sludge particles of about 3, 2 and 1 cm size retrieved from the stainless steel reactor by means of the basket after devolatilization (black particles) and complete char burn-out (brown particles). The fluidized bed consisted of quartzite in the size range 150–300 μm operated at a gas superficial velocity of 0.25 m/s (i.e. in the same operating conditions of Fig. 2). The main finding is that particles undergo negligible fragmentation after both devolatilization and combustion: only one fragment was retrieved by means of the basket at the end of the tests. It is worth recalling that fragments smaller than about 0.8 mm, i.e. the mesh openings, could not be retrieved by the basket.

Further analysis of the micrographs indicates that fuel particles shrunk by a factor of about 0.75–0.8 after both pyrolysis and combustion, whereas the weight loss is in agreement with the data obtained with the proximate analysis: fixed carbon and ash content 1.0 and 6.7%w, respectively.

Char particles are very porous. This is confirmed by inspection of Fig. 4. Micrographs in Fig. 4 show the cross-sections of ash and char particles about 1 cm size embedded in epoxy resin and then cross-cut. Post-processed images of these micrographs are also reported in Fig. 4. Both ash and char particles exhibit a highly anisotropic pore structure characterized by large pores and cavities and by a coherent outer layer which, probably, preserves the structural integrity of the particles. The key difference between ash and char particles is that the ash internal structure is more porous: the multiple large cavities present in the char particle apparently give rise to a single large cavity upon complete burn-off. Micrographs in Fig. 4A and B were further analyzed by a post-processing software in order to estimate the void fraction across the cross section. Post-processed images, reported in Fig. 4C and D, indicate void fractions of about 0.84 and 0.7 for ash and char particle, respectively.

Additional details of the physical structure of the sewage sludge particle after pyrolysis and combustion are revealed by SEM inspection. Fig. 5 reports micrographs obtained by SEM observation of ash

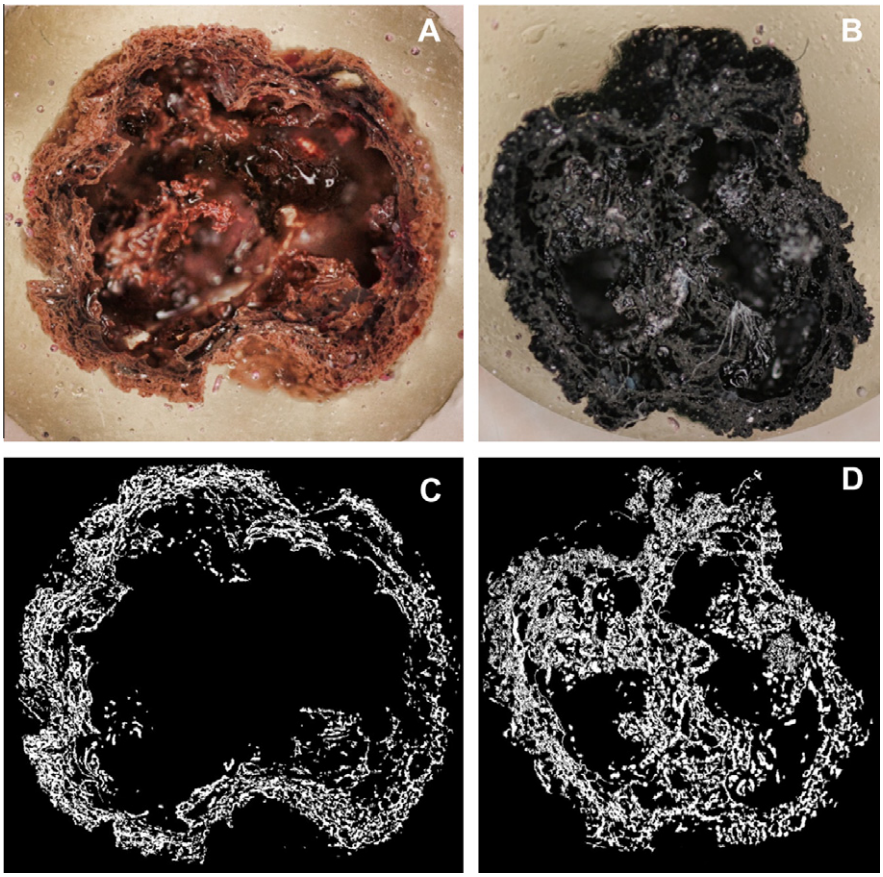

Fig. 4. Images of the internal structure of two sludge particles after tests of devolatilization and char burn-out (A) and pyrolysis (B) and the resulting post-processed images (C and D, respectively).

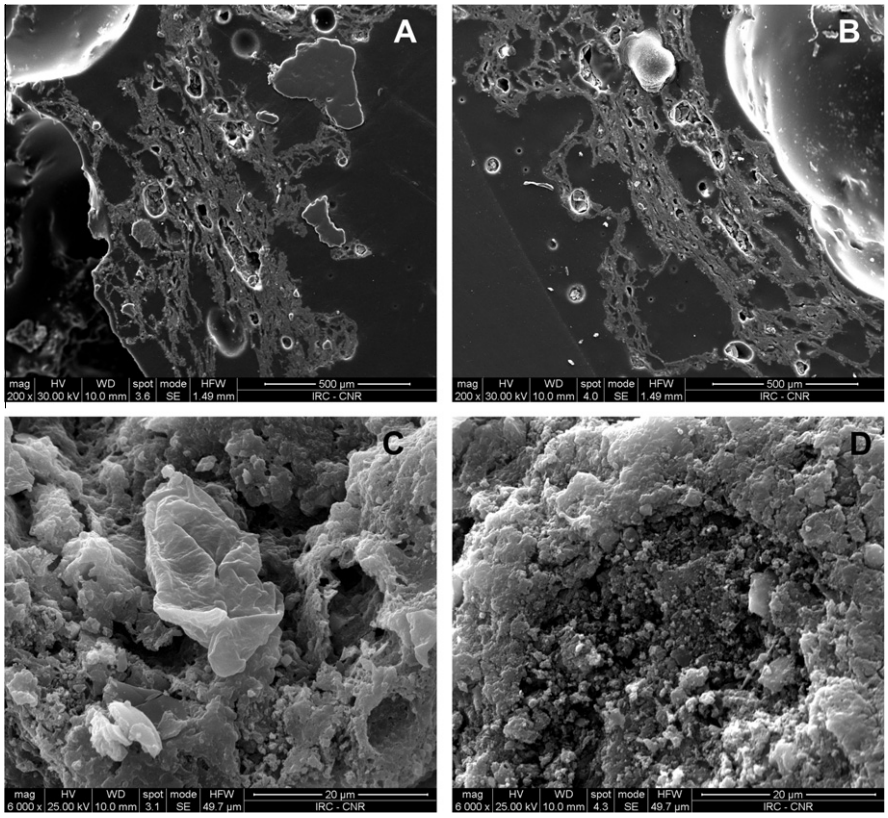

Fig. 5. SEM images of the internal structure and external surface of outer layer of two sewage sludge particles after combustion (A and C, respectively) and pyrolysis (B and D, respectively).

Table 2
Normalized ash chemical composition.

	Ash analysis (‰) (on ash basis)				
Analysis	ICP-MS	SEM/EDX			
Region	Sample	Outer layer		External surface	
Material	Fuel (a.r.)	Ash	Char	Ash	Char
Na	0.7	1.2	0.9	3.6	1.3
Mg	3.1	3.3	2.0	4.4	2.5
Al	37.8	39.9	43.0	36.9	31.6
P	18.7	23.7	21.8	19.2	18.1
K	3.2	3.3	4.2	3.5	2.9
Ca	20.7	15.5	14.7	15.7	22.1
Ti	0.3	1.1	1.1	1.5	5.7
Cr	0.7	0.5	1.0	1.3	0.8
Fe	12.4	9.2	9.0	10.3	12.3
Ni	2.3	2.2	2.3	3.4	2.7

and char particles of about 1 cm size. Analysis of the cross section and of the external surface of the particles confirms that the outer layer of ash and char particles consists of a porous coherent structure of partially fused material characterized by a thickness of about 500 µm. The EDX analysis of these samples is reported in Table 2, compared with the ICP-MS ash analysis of the as-received fuel. Altogether, the chemical composition of ash obtained by SEM-EDX is very similar to that measured by ICP-MS on the as-received fuel sample. In particular, it can be observed that the major elements initially present in the as-received sewage sludge are still present in the char and ash particles at approximately the same concentration. The only exceptions are apparently represented by a slightly lower concentration of Fe and Ca in the char and in the ash particle, possibly due to the volatilization of $CaCl_2$ and $FeCl_3$ during thermal processing.

The effect of particle comminution phenomena on patterns of fuel devolatilization/pyrolysis and char burn-out of a single particle of sewage sludge at 850 °C has been assessed by combining the analysis of the time series of gas concentration measured at the exhaust and the observation of char and ash samples retrieved from the bed. Fig. 6 reports the time series of gas concentrations ($CO, CO_2, SO_2, NO, H_2, CH_4$) at the exhaust recorded during three selected pyrolysis tests, each with a single fuel particle feeding. The bed material was quartzite in the size range 150–300 µm fluidized at a gas superficial velocity of 0.4 m/s. Three fuel particles with initial average size of about 12, 22 and 28 mm showed negligible particle fragmentation after pyrolysis, as demonstrated by observation of particles retrieved from the bed by means of basket.

The analysis of the time-resolved gas concentrations at the exhaust indicates different release profiles of the gaseous species along the test: earlier release for NO and CH_4, later for H_2 and CO, intermediate for CO_2 and SO_2. The time-resolved CO_2 concentration profile has been assumed to estimate the pyrolysis time corresponding to 95% cumulative release. This value resulted in 150, 300 and 340s for fuel particles of 12, 22 and 28 mm size, respectively. As expected, the pyrolysis time is longer, the coarser the particle.

Fig. 7 compares the time series of gas concentrations (CO, CO_2, NO) measured in combustion tests carried out with un-fragmented (12.7 and 22.8 mm size) and fragmented (21.8 mm size) fuel particles. Particle devolatilization and overall burn-out times have been estimated by analysis of the time series of CO_2 concentration and cumulative CO_2 release. For the un-fragmented particles the devolatilization time were of 110 and 250s for 12.7 and 22.8 mm fuel particles respectively, while the complete burn-out times were 160 and 360s, respectively. For the fragmented particle the devolatilization and complete burn-out times were 160 and 230s, respectively.

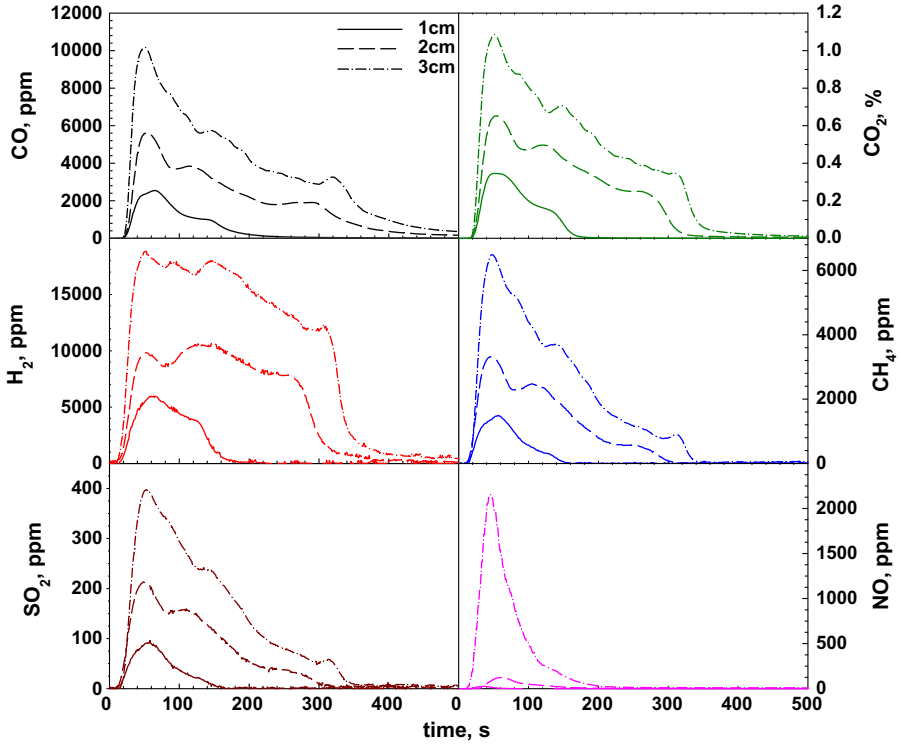

Fig. 6. Time-resolved CO, CH_4, H_2, SO_2, NO and CO_2 concentration during pyrolysis experiments carried out with single un-fragmented sewage sludge particles characterized by different initial size. Initial fuel size: 12.4, 22.1 and 27.8 mm.

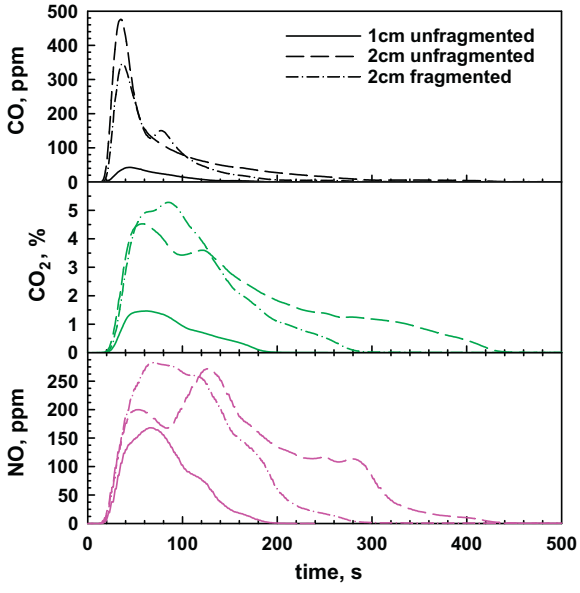

Fig. 7. Time-resolved CO, NO and CO_2 concentration during combustion experiments carried out with single un-fragmented sewage sludge particles (initial size: 12.7 and 22.8 mm) and with a 21.8 mm fragmented sewage sludge particle.

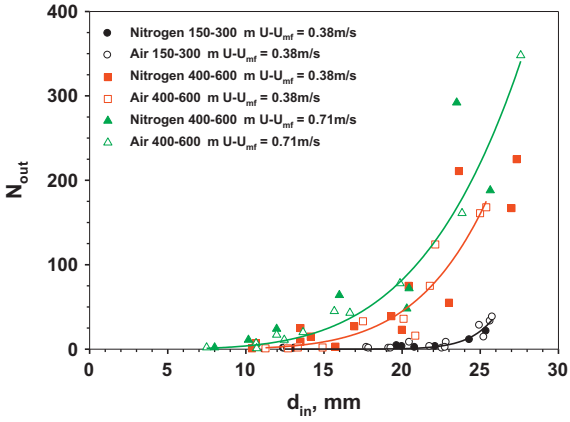

Fig. 8. Multiplication factor as a function of average initial size of the fuel particle for different operating conditions.

The comparison between results of combustion and pyrolysis tests (Figs. 6 and 7) suggests that: (i) the CO_2 concentration profile presents a pronounced shoulder at the end of the combustion process due to char burn-out; (ii) the devolatilization time is smaller than the pyrolysis time, indicating that – even without the establishment of a flame – combustion of volatile matter emphasizes the devolatilization kinetics; (iii) particle fragmentation reduces both devolatilization and char burn-out times.

The influence of bed material size and gas superficial velocity on particle fragmentation has been assessed during both pyrolysis and combustion of sewage sludge. Figs. 8 and 9 report the number (N_{out}) of particle fragments collected after experiments carried out with a single particle (i.e. the particle multiplication factor) and the average size (d_{out}^{max}) of the coarsest fragment collected at the end of pyrolysis and of combustion tests. Both variables are reported as a function of the size of the fuel particle d_{in}. Experiments were carried out with quartz sieved in the size range 150–300 μm at a gas superficial velocity of 0.4 m/s and with quartz sieved in the size range 400–600 μm at gas superficial velocities of 0.47 and 0.8 m/s. Results reported in Figs. 8 and 9 indicate that both N_{out} and d_{out}^{max} do not significantly depend on the oxidative (air, combustion tests) vs. non-oxidative (nitrogen, pyrolysis tests) nature of the environment. This

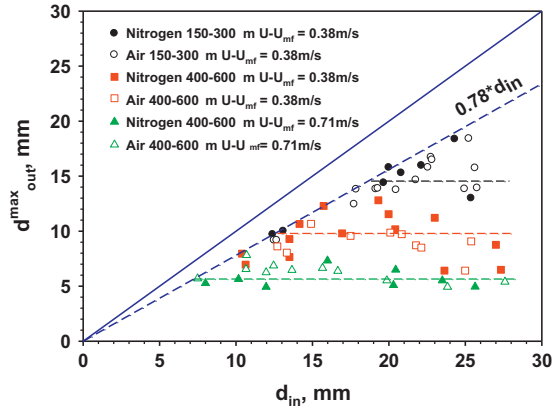

Fig. 9. Average size of the coarsest fragment produced by the particle fragmentation as a function of average initial size of the fuel particle for different operating conditions.

result further supports the conclusion that particle fragmentation occurs mainly during drying and pyrolysis/devolatilization, with a very limited extent of fragmentation occurring during char burn-out. It is likely that the limited content of fixed carbon in char of the tested sewage sludge, finely dispersed into the ash matrix, gives a limited contribution to the connectivity and the mechanical resistance of the fuel particle during char burn-off.

Analysis of the trend of the particle multiplication factor vs. d_{in} for tests carried out with quartzite in the size range of 150–300 μm and operating the bed with a fluidization velocity of 0.4 m/s ($U - U_{mf}$ = 0.38 m/s) shows that: (i) there exists a critical threshold (d^c_{in}) of fuel particle size, in the order of 18–20 mm, below which sewage sludge particles do not fragment; (ii) N_{out} strongly increases with the initial fuel particle size once d_{in} exceeds d^c_{in}. As the bed material size is increased (400–600 μm) – while keeping constant the excess gas superficial velocity (U = 0.47 m/s and $U - U_{mf}$ = 0.38 m/s) – N_{out} shows a similar behavior as a function of d_{in}, but with a smaller value of d^c_{in}, in the order of 11–12 mm. N_{out} strongly increases with bed material size, for $d_{in} > d^c_{in}$. Notably, unfragmented particles collected during tests carried out with the finer bed material (150–300 μm) turned out to be completely filled with bed solids, which eventually escaped from the cavities of the char particle by gentle shaking. This phenomenon was not recorded in tests carried out with the coarser bed material (400–600 μm). It is likely that filling of char particles with bed solids might have made them less prone to fragmentation as compared with empty ones.

Increasing the excess gas superficial velocity (U = 0.8 m/s and $U - U_{mf}$ = 0.71 m/s) – while keeping constant the bed solids size (400–600 μm) – lead to the following findings: (i) N_{out} increases with d_{in}, with an even further reduction of d^c_{in} to nearly 7–8 mm; (ii) N_{out} undergoes a moderate increase with excess gas superficial velocity, for $d_{in} > d^c_{in}$.

Fig. 9 reports the average size of the coarsest generated fragment d^{max}_{out} (including the case of unfragmented particles) as a function of the initial average size d_{in} of the fuel particle. It can be observed that, whatever the operating conditions: (i) d^{max}_{out} varies with d_{in} according to the linear relationship $d^{max}_{out} = 0.78\ d_{in}$, as far as $d_{in} < d^c_{in}$, a trend consistent with particle shrinkage in absence of fragmentation; (ii) d^{max}_{out} is substantially unaffected by d_{in} for $d_{in} > d^c_{in}$, d^{max}_{out} levelling off at values of 15, 10 and 5 mm for tests carried out with 150–300 μm quartz at $U - U_{mf}$ = 0.38 m/s, with 400–600 μm quartz at $U - U_{mf}$ = 0.38 m/s and at $U - U_{mf}$ = 0.71 m/s, respectively. Correspondingly, the size of the largest fragment decreases with increasing bed material size and excess gas superficial velocity with respect to incipient fluidization as $d_{in} > d^c_{in}$.

4. Conclusions

The phenomenology of devolatilization and char burn-out of lumps of wet sewage sludge in bubbling fluidized beds has been investigated by visual observation in a quartz bench-scale fluidized bed reactor, by continuous monitoring of gas concentrations in gas effluents and by periodic retrieval of fuel particles from the bed by means of a basket.

Fuel particle display a pronounced tendency to segregate on top of the bed during devolatilization. The released volatile matter burns in the freeboard in a flameless fashion, presumably due to the extensive release of moisture present in the fuel particle. Despite the plastic nature of the raw sewage sludge and the extensive shear experienced in a freely bubbling fluidized bed, lumps of wet sludge undergo limited apparent deformation and mostly keep their original shape – apart from possible occurrence of fragmentation. SEM/EDX and image analysis of un-fragmented char and ash particles showed the formation of balloon-like particles, consisting of a porous coherent outer layer embodying big internal cavities. The content of inorganics in ash and char particles is similar to that measured in the as received fuel.

Periodic retrieval of fragmented and un-fragmented particles from the bed by means of the basket enabled the measurement of the particle multiplication factor N_{out} and of the size d^{max}_{out} of the coarsest generated fragment. These variables have been related to the initial size of the fuel particle, to the size of bed solids, to the excess gas superficial velocity with respect to incipient fluidization. It was observed that particle fragmentation occurs mainly during drying and pyrolysis/devolatilization, with a very limited occurrence during char burn-out. Fuel particles smaller than a limit size d^c_{in} do not undergo fragmentation. Beyond d^c_{in}, the multiplication factor is a strong function of the initial particle size. Increasing bed solids size yields a pronounced increase of the particle multiplication factor and a decrease of the limit size at the onset of fragmentation. Similar, but less pronounced, effects are observed as the excess gas superficial velocity is increased. Occurrence of particle fragmentation reduces the devolatilization/pyrolysis and char burn-out time scales.

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